

Impact of subsolar metallicities on photometric redshifts

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ABSTRACT

With the advent of deep photometric surveys the use of photometric redshifts, obtained with a variety of techniques, has become more and more widespread. Giving access to galaxies with a wide range of luminosities out to high redshifts, these surveys include many faint galaxies with significantly subsolar metallicities.

We use our chemically consistent (CC) galaxy evolutionary synthesis code *GALEV* to produce a large grid of template spectral energy distributions (SEDs) for galaxies of spectral types E and Sa through Sd – one accounting in a CC way for the increasing initial metallicities of successive stellar generations, the other one for exclusively solar metallicities – for comparison.

We use our new photometric redshift code *GAZELLE* based on the comparison of observed and model SEDs. Comparing the photometric redshifts obtained using solar-metallicity templates when working on a catalogue of artificially created CC SEDs, typical for low-metallicity local late-type galaxies and for intrinsically low-luminosity, and hence low-metallicity, galaxies in the high-redshift universe, we find a significant bias resulting from this metallicity mismatch. This bias consists of a systematic underestimate of the photometric redshift by typically $\Delta z \approx 0.1 \dots 0.2$ until $z \approx 1.2$, depending on galaxy type, of distant, faint and low-metallicity galaxies if analysed with solar-metallicity templates.

Key words: galaxies: abundances – galaxies: distances and redshifts – galaxies: evolution – galaxies: high-redshift.

1 INTRODUCTION

Most of the present-day studies of large samples of high-redshift galaxies rely on photometric redshifts comparing observed spectral energy distributions (SEDs), i.e. magnitudes and colours in multiple filters, to a set of templates. For that reason, the choice of the right set of template is crucial to determine accurate and unbiased photometric redshifts. The most widely used templates are either observed local templates, e.g. from Coleman, Wu & Weedman (1980), that do not include any evolutionary correction, or templates generated with evolutionary synthesis models which in most cases use fixed solar metallicities.

During recent years, evidence has accumulated that galaxies are not made out of stars of one metallicity, but show a wide range from very metal-poor to more metal-rich stars. This holds true not only for our Milky Way (Rocha-Pinto & Maciel 1998; Ak et al. 2007), but also for external galaxies like e.g. the Large Magellanic Cloud (LMC) (Cole, Smecker-Hane & Gallagher 2000) and giant ellipticals like NGC 5128 (= Centaurus A, Harris, Harris & Poole 1999; Harris & Harris 2000).

Studying samples of local star-forming galaxies, Skillman, Kennicutt & Hodge (1989) showed a trend of decreasing average

metallicity of a galaxy with decreasing luminosity, used as an indicator of its mass, and spanning more than 12 mag in luminosity. Larger samples, compiled for example from the Sloan Digital Sky Survey (SDSS) (Tremonti et al. 2004; Kewley & Ellison 2008), confirmed this mass–metallicity relation and extended it to even lower masses (Lee et al. 2006).

This is particularly important with respect to high-redshift galaxies in the early Universe, since those galaxies did not yet have the time to produce enough stars to enrich their interstellar medium (ISM) to high metallicities. Studies of Lyman break galaxies (Pettini et al. 2001), damped Lyman α absorbers (Prochaska et al. 2003) and gamma-ray bursts (Prochaska et al. 2007) all show that galaxies get progressively more metal-poor if they are observed at high redshift. Furthermore, dwarf galaxies, such as the LMC, that are metal-poor in the local Universe, are observable out to considerable redshifts in deep imaging surveys. Note that Erb et al. (2006) found a mass–metallicity relation for galaxies at redshifts of $z \approx 2$, confirming that the local trend was already established in the early Universe.

For that reason, evolutionary synthesis models that take the chemical enrichment of successive stellar generations into account are principally superior to more simplified models with fixed metallicity. In Bicker et al. (2004), we showed that with appropriate star formation histories our chemically consistent (CC) *GALEV* models agree well with a wealth of observed properties for local and high-redshift

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galaxies, and showed how the presently observed stellar metallicity distributions in galaxies have evolved. In Bicker & Fritze (2005), we demonstrated the impact on non-solar metallicities on the determination of star formation rates (SFRs) from emission lines and ultraviolet (UV) fluxes. Kodama, Bell & Bower (1999) have shown that metallicities can have a significant impact on observed colours of high-redshift galaxies; the impact of metallicity on rest-frame colours was studied by other authors. However, the impact of those generally bluer colours on photometric redshifts has not been studied so far. In this Letter, we quantify the impact of neglecting those subsolar metallicities on photometric redshifts.

2 CREATION OF TEMPLATE SEDs

2.1 Input models

To study the chemical enrichment history of the common spectral galaxy types E and Sa through Sd, we used our CC galaxy evolution code *GALEV*. Assuming a closed-box model, *GALEV* allows us to compute the chemical enrichment of a galaxy's gas-reservoir from the yields of dying stars. We use isochrones from the Padova-group (Bertelli et al. 1994) with metallicities ranging from $[\text{Fe}/\text{H}] = -1.7$ to $+0.3$ and a Salpeter initial mass function (IMF) (Salpeter 1955) with mass limits of 0.10 and $100 M_{\odot}$. Note that a different choice of the IMF, for example Kroupa or Chabrier, does not affect the results obtained below. The spectral galaxy types are characterized by an exponentially declining SFR for the E-model, SFRs proportional to the available gas mass for the Sa–Sc models (with factors of proportionality decreasing towards later types), and a constant SFR scenario for the Sd. These star formation histories were shown to provide a good match to present-day galaxy templates, for example from Kennicutt (1992) in Bicker et al. (2004). To derive the effects on photometric redshifts, we also ran all those models again, this time fixing the metallicity to the solar value $[\text{Fe}/\text{H}] = 0.0$. Our *GALEV* models also include line and continuum emission from ionized gas, with line strength appropriate for the particular gaseous metallicity at each time. The importance of emission lines for accurate photometric redshifts has recently been shown by Ilbert et al. (2008).

To derive the SEDs for comparison with observations, we redshifted the spectra at all time-steps to the redshift corresponding to the age of each galaxy spectrum, adopting a concordance cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.30$ and $\Omega_{\Lambda} = 0.70$. We assume that all galaxies started forming stars at $z = 8$. Variations of this formation redshift with spectral type, as for example suggested by Noeske et al. (2007a,b) for the latest spectral types, have little effect on the present study since those show little evolution anyway. This means we consistently account for both evolutionary and cosmological corrections. Since some galaxies at high redshifts are found to contain significant amounts of dust (e.g. Steidel et al. 1999), we convolve each spectrum with the dust attenuation curve of Calzetti et al. (2000). We chose a range of extinctions from $E(B - V) = 0.0$ to 0.5 mag in steps of $\Delta E(B - V) = 0.05 \text{ mag}$. We include the effects of intergalactic absorption following Madau (1995) and then convolve each spectrum with a set of typical filters, here taken to be the SDSS *ugriz* and the standard Two-Micron All-Sky Survey (2MASS) *JHK* filters. Galaxies were normalized as to show by $z = 0$, the average observed Johnson *B*-band magnitudes for their respective types as given by Sandage, Binggeli & Tammann (1985a,b). We then added the bolometric distance modulus for each redshift. This results in a total of ≈ 3200 template SEDs with smaller redshift intervals at lower z and wider sampling at high

redshifts for each of our 10 models (five types E, Sa–Sd, all CC and with metallicity fixed to solar for comparison).

2.2 Addition of noise

To simulate real observations, we added Gaussian noise observational errors to each magnitude. The amount of scatter added, Δm_i , depends on the magnitude m_i of the i th filter:

$$\Delta m_i = a + b \times \exp(c \times m_i - d),$$

with $a = 0.03 \text{ mag}$ describing calibration or zero-point uncertainties, $b = 3.75$ and $c = 0.75$ being constants defining the shape of the curve. d depends on the depth of the underlying observations, here chosen to correspond to 5σ limiting *AB* magnitudes of (26, 27, 27, 27, 26, 25, 25, 24) mag for the (*u, g, r, i, z, J, H, K*) filters. This procedure was repeated 100 times for each input SED, resulting in an artificially created input catalogue of $\approx 7 \times 10^5$ galaxies for each model. For the following analysis, we then derived median values and 1σ uncertainties in bins of $\Delta z = 0.05$.

2.3 Determining photometric redshifts

To derive the photometric redshifts, we use our photometric redshift code *GAZELLE* described in more detail in a companion paper (Kotulla & Fritze, in preparation). In principle, it uses a χ^2 algorithm to compare fluxes derived from the observed SEDs with a range of template SEDs. The resulting χ^2 values are then transformed into normalized probabilities. Masses are derived by scaling the model SEDs as a whole to match the observed SED on average. To determine 1σ uncertainties for redshifts and all dependent parameters (masses, SFRs, metallicities, etc.), we derive the minimum and maximum values encountered while summing up normalized probabilities (from highest to lowest) until 68 per cent have been reached. We restrict our template set to only undisturbed galaxies E, and Sa through Sd, since those are well calibrated against observed galaxy templates, and match observations in colours, spectra and metallicities (see Bicker et al. 2004; Kotulla et al. 2008, for a detailed comparison).

In the following, we will focus on the redshift determination and the best-match χ^2 value.

3 RESULTS

3.1 Evolution of metallicity with redshift

In Fig. 1, we present the metallicity evolution of the different spectral galaxy types E, Sa and Sd with decreasing redshift. We show two different metallicity measures: the gas phase or ISM metallicity and the luminosity-weighted stellar metallicity in a set of different rest-frame filters. The ISM metallicity is traditionally measured from emission lines, while stellar metallicities are derived from stellar absorption lines, as for example Lick indices (e.g. Trager et al. 1998; Schiavon et al. 2006), requiring spectra of much higher signal-to-noise ratio. Our models yield metallicities at $z = 0$ of $Z_E = Z_{\odot}$, $Z_{\text{Sa}} = 1.5 Z_{\odot}$ and $Z_{\text{Sd}} = 0.25 Z_{\odot}$, in good agreement with observed metallicities, for example from Zaritsky, Kennicutt & Huchra (1994).

The most important point with respect to this paper, however, is that only the E and Sa models reach enrichment levels comparable to solar metallicity. Later spiral types, i.e. the Sb–Sd models, only reach significantly subsolar metallicities after a Hubble time, rendering the assumption of solar metallicity independent of redshift

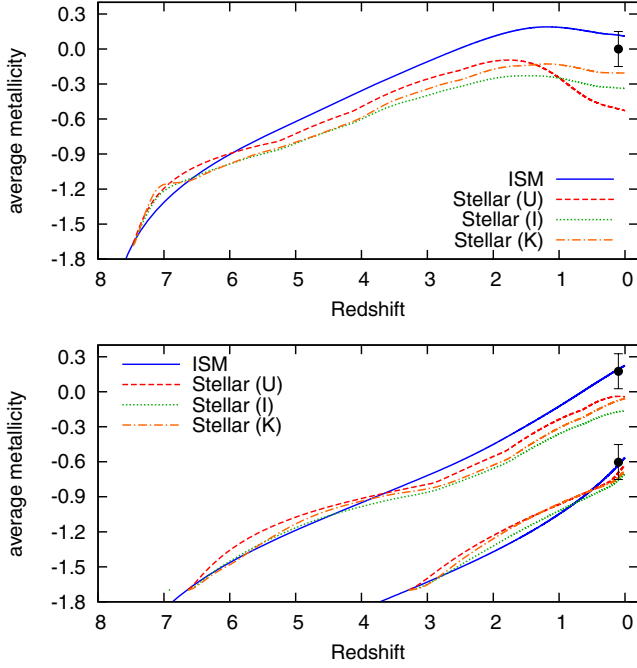


Figure 1. Chemical enrichment histories for galaxies of different spectral types E (top panel), Sa (lower panel, upper curves) and Sd (lower panel, lower curves). The blue solid lines mark the gas phase or ISM metallicity, while the dashed lines represent luminosity-weighted stellar metallicities in different bandpasses. Black points mark observed metallicities (Zaritsky et al. 1994) of local galaxies.

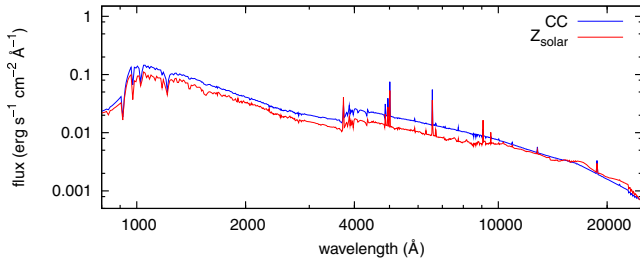


Figure 2. Spectrum of a 4 Gyr old constant SFR model (Sd) calculated in the CC way (upper blue curve) and the fixed solar metallicity only way (lower red curve), both having identical masses.

and galaxy type invalid. While solar metallicity is a moderately good approximation [$Z(t) > 0.5Z_{\odot}$] for early-type galaxies (E to Sa) back to fairly young ages or high redshifts, it becomes less and less valid for later galaxy types, in particular at earlier times or higher redshifts.

Low-metallicity stellar populations are brighter in the optical and UV (cf. Fig. 2), have bluer colours (since their stars are hotter), and produce more ionizing photons compared to their equal-mass solar-metallicity counterparts. This leads to higher emission line fluxes and hence an overestimation of SFRs by up to factors of ≥ 2 (Bicker & Fritze 2005) if solar-metallicity calibrations are used. At the same time, their higher overall luminosities lead to overestimations of galaxy masses by up to factors of ≥ 5 and their bluer colours lead to an underestimation of their stellar population ages by factors up to ≥ 2 , unless their subsolar metallicities are properly taken into account.

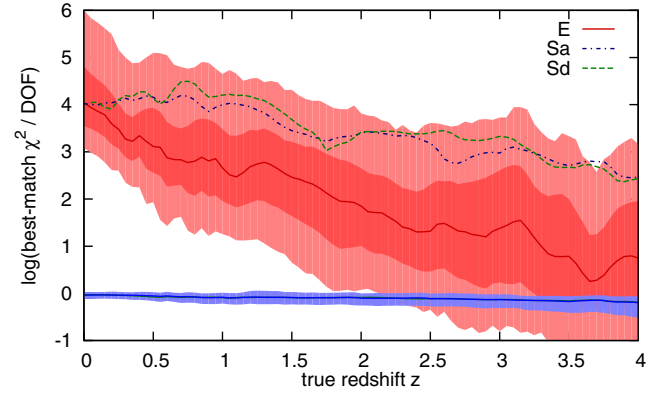


Figure 3. χ^2 value per DOF of best-matching galaxy–template combination as a function of redshift for three different galaxy types E (solid, red line), Sa (blue dash-dotted line) and Sd (green dashed line). In all three cases, we used solar-metallicity templates and CC input galaxies. Dark and light red shaded regions mark the 1σ and 3σ ranges for the E-type model. The blue shaded region marks the outcome of the matched template runs (solar versus solar and CC versus CC).

3.2 Impact on photometric redshifts

We ran three different sets of photometric redshift determinations, comparing (a) the solar-metallicity SED catalogue to solar-metallicity SED templates, (b) the CC SED catalogue to CC SED templates and (c) analysing the CC SED catalogue using solar-metallicity SED templates. The outcomes of runs (a) and (b) are shown by the green and blue lines and symbols in Figs 3 and 4; every data point represents the median value in bins of $\Delta z = 0.05$ in redshift. As expected, we find very small χ^2 values for the best match and excellent correspondence between true and photometric redshifts. The third run analysing the CC catalogue with solar-metallicity templates mimics the wide-spread analysis method for observation of low-metallicity galaxies in the early Universe using close to solar-metallicity SED templates. Those can either be locally observed galaxies that naturally have higher metallicities than their high-redshift counterparts, training sets of galaxies with available spectroscopic redshifts (and hence the brightest and with the mass–metallicity relation also most metal-rich galaxies at each redshift) or solar-metallicity model templates. The results are shown as red symbols in both figures. As expected, the best-match χ^2/DOF values [where degrees-of-freedom (DOF) means the number of filters] for run (c) are significantly larger at almost all redshifts. The trend towards smaller χ^2 values at higher redshifts can be understood as a consequence of photometric uncertainties increasing with decreasing brightness and finally a decreasing number of filters due to dropouts and magnitudes falling below the detection limit. This in turn allows more flexible matching by varying both shape, determined by galaxy type, redshift and extinction, and normalization, that is galaxy mass, of the template SED.

Fig. 4 shows the offsets between true and retrieved photometric redshifts that result from the choice of templates not matching the observed metallicities. We also show the 1σ regions for each galaxy type as filled regions. It is obvious that even for the near-solar-metallicity galaxy types E and Sa, there are still significant offsets of $\Delta z = z_{\text{phot}} - z_{\text{spec}} \approx -0.1$ [equivalent to $\sigma_z = \Delta z/(1+z) \geq -0.05$] until $z \approx 1.2$. At higher redshifts $z = 1.5 \dots 2.8$, we also find a bias but this is less prominent than at lower redshifts, in particular, compared to the increased scatter at those redshifts. At even higher redshifts $z \gtrsim 3$ dropouts start to dominate the redshift determination.

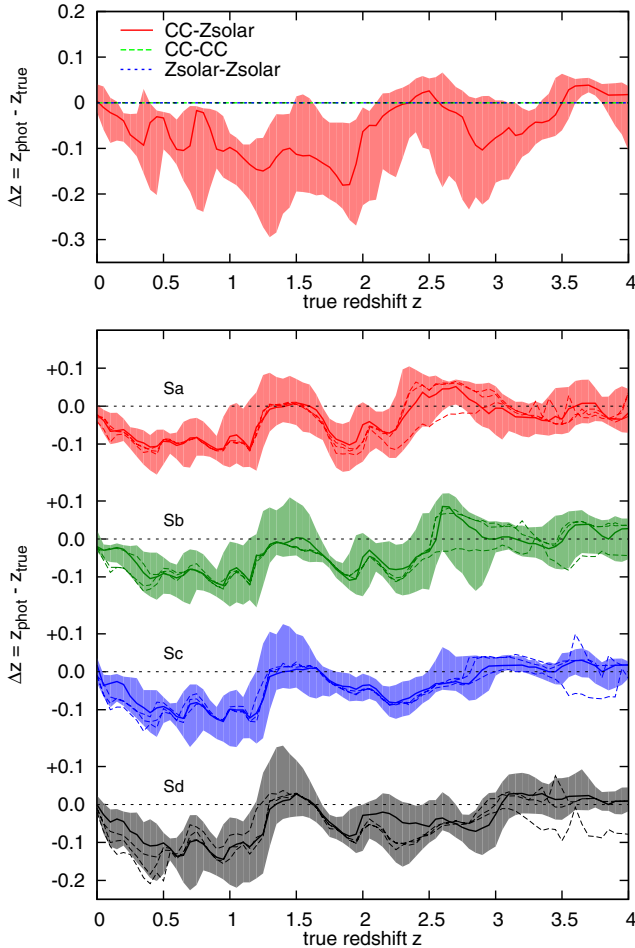


Figure 4. Redshift offset $\Delta z = z_{\text{phot}} - z_{\text{true}}$ for the elliptical (top panel) and spirals Sa, Sb, Sc, and Sd (lower panel). In the top panel, blue and green lines are for matching combinations, red symbols show the errors resulting from the use of solar-metallicity templates for the analysis of lower metallicity galaxies. Each point represents the median value in a bin of width $\Delta z = 0.05$. The dashed lines in the lower panels show the bias for $E(B - V) \leq 0.1$ mag.

The reason for these biases is that although the metallicity is near solar for the early types E and Sa, the galaxy nevertheless contains a large fraction of lower metallicity stars (e.g. $\approx 2/3$ of the U -band flux of nearby elliptical galaxies is emitted by stars with $[\text{Fe}/\text{H}] \leq -0.7$; Bicker et al. 2004). As a general trend, the retrieved photometric redshifts show a bias towards lower redshifts. This trend can be understood from the bluer SEDs of the CC models, generated by the lower metallicity stars, that the photometric redshift code tries to compensate for by attributing lower redshifts to its Z_{\odot} templates. This offset is, in particular at low redshifts $z \leq 1$, larger than the typical scatter of $\sigma_z \leq 0.03$ found for large samples of photometric redshifts (e.g. Mobasher et al. 2007).

Furthermore, the amount of dust reddening also plays a role in the following sense: essentially, dust-free models with $E(B - V) < 0.1$ mag have larger best-match χ^2 values and are more strongly biased towards too low redshifts than models with more dust, reaching a maximum for the Sd-type galaxy at $z \approx 0.4$ where $\Delta z = -0.2$ or equivalently $\sigma_z = 0.14$ (see dashed lines in Fig. 4). This point is particularly crucial at $z \gtrsim 1$, where we essentially observe the rest-frame UV. We here are biased towards UV-bright objects, i.e.

those that are *not* hidden behind large amounts of dust. Photometric redshifts obtained by fitting solar-metallicity templates to those galaxies are therefore even more strongly biased towards too low redshifts than the median of all extinctions presented above.

Observational evidence for the bias described here can be found, for example, in Ilbert et al. (2006, fig. 3). There observed templates were used to derive photometric redshifts from a filter set similar to the one used here, and an underestimation until $z \approx 0.6$ and in particular at $z_{\text{phot}} = 0.3$, $z_{\text{spec}} = 0.4$ was found.

4 CONCLUSIONS AND SUMMARY

We used our CC galaxy evolutionary synthesis models GALEV to study the chemical enrichment histories of galaxies over a range of spectral types E and Sa through Sd. The E-type galaxy reaches enrichment levels of $Z > 0.5 Z_{\odot}$ already at high redshifts $z \approx 4$ and remains almost from there on. Sa-type galaxies are significantly subsolar at $z \gtrsim 1.5$, while later types such as Sd even after a Hubble time only reach levels of $1/4 Z_{\odot}$.

This fact, in combination with observational evidence for a wide range in stellar metallicities of our and nearby galaxies and the decreasing stellar metallicities in galaxies at higher redshifts, casts doubt on widespread methods of using only solar-metallicity templates to derive photometric redshifts from observed SEDs. We study the impact of the increasing importance of subsolar-metallicity populations in high-redshift galaxies on photometric redshift determinations using our photometric redshift code GAZELLE on several large synthetic galaxy catalogues, and find a significant bias of $\Delta z \approx 0.1$ for galaxies at $z \leq 1.2$ towards systematically underestimated photometric redshifts as a consequence of their bluer SEDs.

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